DESIGN TOOLS FOR LIFE CYCLE ANALYSIS AND DURABILITY EVALUATION OF BUILDING SYSTEMS: A RESEARCH ON THE BUILDING ENVELOPE

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ABSTRACT

The behavior and service life prediction of building systems requires to develop tools to assist the designer. The paper is focused on a research carried out in the Department of Architecture and Design with the Department of Mathematical Sciences of the Politecnico di Torino. The goal is to develop a design tool to forecast the building subsystem durability and to help the designer in design options. The method is based on FMEA (Failure Mode and Effect Analysis) developed in a qualitative way as well as in a probabilistic way. The analyst assess the functional models, the failures and the consequent predicted service life of components. The designer will select materials defining the risk coming from environmental agents, design, materials and workmanship. The estimated service life has been assessed by Monte Carlo method. The external walls was the example tested using data by investigations in the area of northern Italy and from literature.

INTRODUCTION

The durability of materials and components is not usually well defined at the design stage. Many times the knowledge of the behavior of the building subsystem in the real use is not available to the designer unless well known by experts. Codes of practice, technical literature on building pathology and durability are not so widespread and easy to find by designers.

The consequence of this lack of information is an overwhelming amount of building failures, damages, maintenance expenses and environmental costs.

The life cycle oriented design requires an accurate forecasting of the durability and conscious design options. Technical solutions and assemblies, products and materials have to be tailored for the specific project, site and environmental agents.

The goal of the research is to give to designers a simple but powerful design tool to evaluate a specific design of a building subsystem (e.g. an external wall) in face of durability and maintenance in a particular circumstance. This design tool shall not give an ultimate evaluation but help the designer in the choice. The factors affecting durability are not simply the materials and products adopted but also the form of the building, the environmental agents (i.e. the climate) and the workmanship skills of the construction firms involved. These factors are different from a site to another, from a project to another and must be evaluated in every specific site and project.

The building subsystem configurations can be easily referred to specific types. In this way could be reasonable to study the behavior and the service life of a defined range of subsystem solutions and save the related data. The library of solutions can be associated with BIM software to optimize the options in regard to materials, products and components durability, reuse capability and performances.

The main objective of the method proposed is to avoid errors in design, construction on site, maintenance. Moreover, the optimization of durability of the system and of the components will allow a reduction of the environmental costs and effects.

THE FMEA IN THE BUILDING DOMAIN

The durability assessment methods are stated by the ISO 15686-2011 *"Buildings and Constructed assets – Service Life Planning–part 1: General Principles"*. Among them the Failure Modes and Effects Analysis (FMEA) is highlighted as a promising method to assess service life and durability. This tool, developed in the electronic as well as in nuclear field, has been proposed in the building domain since the past decade (Talon A., 2005;Pollo R., 2006). Many efforts have been made to build up a quantitative method based on FMEA but the goal seems still unreached and the methodologies proposed appear still on test.

The FMEA allows to easily identify in a quite complete manner, failures their causes and consequences. This feature pushed the use of this method above all in a qualitative way. Such a tool is commonly used to evaluate and improve design of industrial plants as well as services management.

The advantage of using FMEA methods are the systematic review of relationship between cause and consequences but it requires a long time to be developed and advanced skills and knowledge are required.

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But, as the researchers know, the modeling of the behavior of a building system in use is fairly difficult. Many are the agents involved and also the functions of the components are not easily defined. Moreover, the building products aren't in many cases certified, and their quality is not well controlled and steady. Anyway, we assume that the quality improvement of the building process towards sustainability will assure a more and more control on materials and products. (i.e. with environmental certifications like EPD).

The FMEA can help to assess the durability of the building subsystems and components and to improve the subsystem design environmental balance. The design options can be optimized improving durability, and consequently reducing energy consumption and emissions, and allowing reuse of the components. This process can be summarized in Figure 1, where the continuous lines are the steps of the process and the dotted are the feedback on the design.

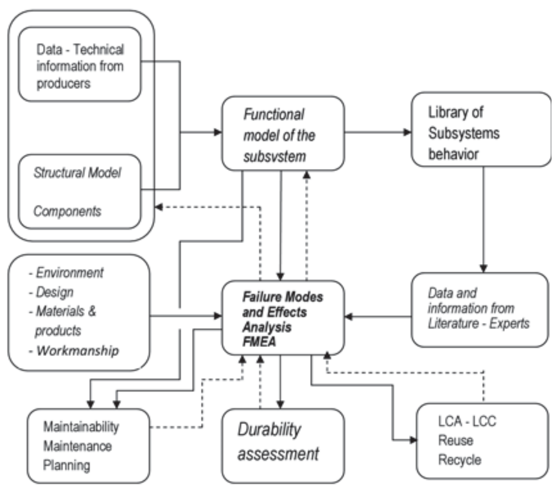

Figure 1 Process of durability analysis

DEVELOPMENT OF THE MODEL

Different building projects are in most cases differently stressed by the environmental agents and users. Moreover, materials used can have specific performances and the workmanship skills can influence the expected service life of the component and of the system. Similarly, the design faults can have severe consequences on the service life. In the analysis we have to consider and evaluate all these factors.

The goal is to allow the designer to analyze, and eventually to compare, design options and materials in a particular environment and with defined skills of the construction firms involved. This situation is quite usual in professional practice but such an analysis is fairly difficult and time consuming.

Thus you need to know how these different elements, like environmental agents, design, material, workmanship affect quality and service life. The designers usually know such information but sometimes dont have a complete knowledge of the behavior of the building subsystem, could be a roof or a pavement or an external wall. Therefore this knowledge is easily accessible on technical literature and codes of practice or can be obtained by the experts.

Moreover the data coming from existing knowledge on the behavior of building systems and materials must be expressed in a feasible way to allow for a quantitative evaluation.

The more simple way to do that is to associate an estimated service life to every cause of failure considering its probability of occurrence. Such a probability will depend on the assessment of the factors of the specific project by the designer. Indeed the designer is usually aware of the specified constraints of the project.

The expected service life due to the failures will be evaluated by the experts and will be a part of the model, considering the effects of causes alone and combined.

The development of this step of the study requires to define a structural and functional model to simulate the service life of subsystems. (Talon A., 2005)

The steps in the process of analysis developed are:

-structural model, requiring the definition of the parts, their links, the environment and use;

-functional model, including the functions identification for each component and for the building product;

-Failure Modes and Effects Analysis, taking account of failures and their consequences on the functionality of the system, of seriousness of the failure and of causes depending on their origin (material performances, environmental agents, workmanship skill);

-Graph of relationship between components based on FMEA results;

-Probabilistic calculation of the expected service life by Monte Carlo method.

The functional model identifies a design solution that can be assumed like a model with a specific behavior in its service life (i.e. a ventilated facade). The specific materials used and their performances will be defined in the specific project and by the designer. According to their characteristics they will comply with their role in a good or in a bad way facing different environments and with a specific design life.

The analysis must be carried out for each function separately (i.e. water tightness, air tightness, heat transfer control, vapour transfer control, etc.).

In the proposed model the FMEA must be carried out by the analyst for the definition of failures, causes and effects on expected service life. The designer, the user of the tool, must evaluate, on a scale of severity, the factors affecting the probability that the failures occur.

The failure probability calculations of the subsystem due by a single cause (identified by the letter T) or by an additive effect (identified by letter S) will be processed by the system.
In this way the input of the model by the designer-user are only the probability estimates of the risk of occurrence of failure coming from:
-design factors;
-materials performance levels;
-environmental agents (more or less severe);
-workmanship skills level.
The scale of severity must be defined by the analyst who defines also the expected service life coming from the specific cause.
In the study is analyzed a simple external wall made by a support masonry layer, a cement render and an acrylic painting (Figure 2).

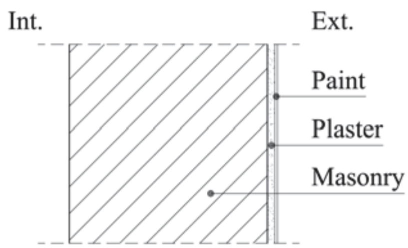

Figure 2 External wall scheme

Data on pathologies and failures of this kind of building subsystem are available in the literature. The reference service life is also defined in a number of publications. (Perret J., 1995) The input data by the designer has been supposed by the authors.
The function investigated is the water tightness of the layers.
A description of the model was made by making use of a specific example and a probability evaluation has been developed.
The model is based on the assumption that different independent competing risks, corresponding to different causes of failure, can reduce the reference service life of a component. The risks are in competition, in the sense that the effective service life corresponds to the occurrence of the first one of the failures, or to the reference service life whenever no failures occur. Different causes of damage can be considered, different components can enter in the models, and the degradation of a component can be one of the possible causes of failure for another one.
Thus, the effective service life of a component is defined as the minimum between independent failure times, each one with its probability of occurrence.
The graphical representation of the model has the purpose to let immediately understand what are the possible causes of failure for each component, what are the components involved in the degradation system, and what are the relationships between components. The basic blocks of the graph describing the system are the nodes, each one corresponding to the service life of a component or the time for a specific failure, and the arrows. Two kind of nodes are considered: round up ones, representing the effective service life of components, and square ones, representing the different causes of failure. Also, two kinds of arrows are admissible: plain arrows entering in round up nodes, describing the competing risks causing the failure of the component, and dashed arrows, entering in square nodes, describing the fact that the specific cause time to failure starts at the occurrence of a component. In the figure 3 is shown the relationship between each component, the round up nodes, of the subsystem, with his estimated service life, with each other.

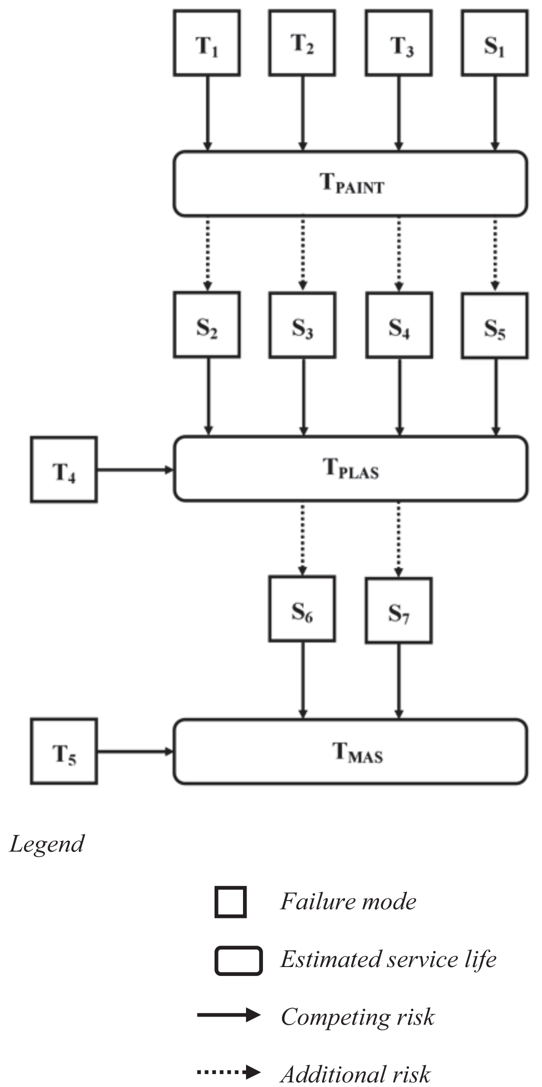

Figure 3 Graph of water penetration phenomena through the wall

Every plain arrow entering in a round up node represents one of the competing causes of failure of the component, and to every plain arrow is associated a string of real values describing the probability of occurrence of the failure and its seriousness in the service life. Arrows can be directed from a component to another, in case that the failure of the first component immediately cause the failure of the second one. On the contrary, the dashed arrows are used to describe the fact that, whenever a component has a failure, a new effect of degradation starts for another component, through a specific competing risk.

Thus, dashed arrows move from component's lifetimes (inside round up nodes) to risks (square nodes).

For every functional system, the model is defined and designed by the analyst, who should consider and represent all possible relationships between components and all possible degradations and the corresponding severities. The string of values describing the probabilities of occurrences of specific failures, are compiled by the user, who assign them considering environmental conditions, characteristic of materials and quality of workmanship.

The string of values associated to each plain arrow (say, e.g., arrow i, corresponding to the specific failure time Ti) contains the information on the possible failure that follows.

- si (seriousness), that is the effective service life in presence of the specific cause of degradation
- pi (probability of design fault), that is the probability that the specific cause of failure occurs in the design of the system. In most of the cases they are assigned equal to 0, when environment or available material ensure that the specific cause of failure can nor occur, or they can be equal 1 in the opposite case. Values between 0 and 1 can be also assigned. Moreover, more than one probability of design fault can be assigned to an arrow (if more concomitant design errors should occur to generate the specific degradation)
- qi (probability of workmanship mistake), that is the probability that an erroneous technical mistake is made in the physical realization of the component. High values of qi are assigned by the user whenever it is sure of a poor workmanship quality.

The probability of the occurrence of failure i, at the time Ti described by seriousness si, is given by pi if it depends only on design faults, or is given by qi if it depends on workmanship mistakes, or on their product if both design faults and workmanship mistake should occur.

Two possible kinds of risks are admitted by the model: major failures, due to the action of severe external agents or to serious design and assembly errors having times denoted by Ti, and failures due to the contemporary non independent causes of physical slow degradation, having times denoted by Sj. As for the other risks, they act in competition to define the service life of the component, and become the effective service life if the corresponding degradation reach a fixed threshold before the other risks. As for risks of the first kind, more than one risk of this second kind can enter a round up node, and they have their own seriousness index. The difference is that times Sj can also depend on failures of some of the components, and that it corresponds a pair of probabilities pj and qj defined as above for each one of the degradation causes that should occur simultaneously.

Considering the system represented in Figure 3, an example of possible strings of values associated to the arrows is given in table 1. This values are defined by the user, who knows the specific environmental and design conditions of the system.

For example, the table provides the following data regarding the component ”External painting”. Its reference service time is 10 (years), and the competing risks $T1$, $T2$, $T3$ and $S1$ (corresponding to ”Meteoric washout”, ”Not suitable weather conditions during the assembly”, ”Not transpiring painting” and a set of slow degradation factors) can reduce it. The failure time $T1$ due to ”Meteoric washout” is set to be 6 years according to the seriousness, and it occurs if both design fault and careless construction occur. All these data about the mentioned failure modes are coming from the FMEA developed for the example.

The probability of design fault $p1$ is the product of the probabilities of failures due to forms, material and environments (0.43 in the example), and the probability $q1$ of workmanship mistake has been set equal to 0.2, so that the probability of occurrence of this risk is the product $p1 \cdot q1 = 0.0128$. Thus, $T1$ is a random life that is equal to the reference service time (10 years) with probability 1-0.0128=0.9872, or equal to 6 with probability 0.0128. The random time $S1$, describing the time for which the slow degradation due to ”Air pollution”, ”Meteoric washout” and ”Not suitable weather conditions during the assembly” reach a fixed threshold, is such that it will be equal to the seriousness 5 if all the three factors occur simultaneously, thus with probability $0.8 \cdot 04 \cdot 0.4 \cdot 0.2 = 0.0256$, and equal to the reference service time 10 with probability $1 - 0.0256 = 0.9744$.

The effective service time of the external painting will be thus the random time $Tpaint$ defined as $Tpaint = \min\{T1;\ T2;\ T3;\ S1\}$. Being a random time, it is described by the list of possible values it can assume, each one with its corresponding probability. These values and the corresponding probabilities can be calculated analytically, through probability calculus, or by using Monte Carlo methods, i.e., generating a set of simulations of the whole system, and using them to estimate possible values and corresponding probabilities.

The values and the corresponding probabilities obtained using a Monte Carlo procedure (with 5000 simulations) for the specific pi and qi in the example are given in table 1.

The random life $Tpaint$ can now be included in the computation of the random effective life of the plaster, *Tplas*, which is defined as *Tplas* = min*{T*4*; S*2*; S*3*; S*4*; S*5*}*. In fact, the risks *S*2*; S*3*; S*4 and *S*5 depend on *Tpaint*, in the sense that the corresponding degradations start at the occurrence of *Tpaint*. Thus, the behaviors of *Tplas* and *Tmas* also can be estimated through a Monte Carlo procedure, simulating realizations of all failure times according to the probabilities and severities given by the user. For our example, the resulting values and probabilities are 4 provided in table 1.

The table also contains some short descriptors of these random times, e.g., their means, medians and percentiles corresponding to 10%. It should be observed that maintenance of components is not included in this simulation. It can be also included, appropriately acting on the dashed arrows (by delaying failure times in case of maintenance of the component). The resulting values and the corresponding probabilities for *Tmas* in this case, again obtained through a Monte Carlo procedure, are given in table 2.

Table 1
Mean value of Predicted Service Life for Paint, Plaster and Masonry, without any maintenance

T_{PAINT}		
Years [n]	Cases [n]	Percentage value [%]
5	113	2,26
6	224	4,48
7	3726	74,53
10	936	18,72
TOT	4999	100,00
Mean value = 7,47		
Median value = 7		
10° perc. = 7		

T_{PLAS}		
Years [n]	Cases [n]	Percentage value [%]
12	15	0,30
13	34	0,68
14	480	9,60
17	127	2,54
20	646	12,92
30	3697	73,95
TOT	4999	100,00
Mean value = 26,67		
Median value = 30		
10° perc. = 14		

T_{MAS}		
Years [n]	Cases [n]	Percentage value [%]
5	471	9,42
14	1	0,02
15	9	0,18
16	108	2,16
19	16	0,32
22	108	2,16
32	615	12,30
60	3671	73,43
TOT	4999	100,00
Mean value = 49,38		
Median value = 60		
10° perc. = 16		

Table 2
Mean value of Predicted Service Life for Masonry, with maintenance

T_{MAS}		
Years [n]	Cases [n]	Percentage value [%]
5	508	10,17
24	3	0,06
27	6	0,12
30	86	1,72
60	4391	87,93
TOT	4994	100,00
Mean value = 53,83		
Median value = 60		
10° perc. = 5		

CONCLUSION

In this paper we suggest a methodology to assess in a relatively simple way the expected service life of building subsystems, as external walls taking account of specific design and form of the building, environmental conditions, materials as well as workmanship level. The model allows the designer to forecast consequences of design options using information and knowledge in the built up procedure by a panel of experts. Such a procedure must be set up by the FMEA analyst on the base of information by codes of practice, literature, products information sheets and expertise.

In this way a database of analysis referred to specific types of subsystems could be put together and adjusted by the experience. Such an experience will be a part of a library of tested solutions by the design firm or by the facility manager. Organisations managing broad estates can be interested to implement this kind of method to improve quality of buildings.

The research requires to be carried out to test the procedure on a range of different building subsystems with specific structural and functional models. The

increase of complexity of subsystem to be investigated will be the challenge for the development of the research.
The results from simulation have given very reasonable results according to the practitioner experience and to the literature. In any case the model must be implemented and tested on a number of real cases.

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